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Construction and Operation of a 10 CFM (Cubic Feed Per Minute) Sampling System with a 10:1 Dilution Ratio for Measuring Condensable Emissions

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CONSTRUCTION AND OPERATION OF A 10 CFM SAMPLING SYSTEM WITH A 10:1 DILUTION RATIO FOR MEASURING CONDENSABLE EMISSIONS

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ABSTRACT

This report describes a transportable sampling apparatus designed to sample incineration sources at municipal and hazardous waste disposal facilities and provide non-contaminated samples of condensable materials. The sample gas, at a flowrate of 10 cubic feet per minute (CFM), passes through a modified Source Assessment Sampling System (SASS) cyclone and is then diluted with clean air at 100 CFM by means of a novel, perforated cone assembly. Rapid uniform dilution takes place through the vigorous mixing of the sample and clean air streams in the dilution chamber. The resultant gas, cooled to approximately atmospheric conditions, is passed through a mixing section that provides a residence time of approximately 3 seconds. The resulting aerosol particles are collected on a Teflon coated glass fiber filter. These solids, along with those collected in the cyclone, are subsequently provided for chemical and biological assay analysis.

CONTENTS

	Page
Abstract	iii
Figures	iv
Tables	v
Metric Conversion Table	vi
1. Introduction	1
2. Detailed Discussion of the System	1
Dilution Air	8
Sample Gas	10
Diluted Gas	10
Outlet Gas	12
Control & Monitoring Assembly	12
3. Assembly and Operating Procedures	15
References	20

FIGURES

1.	Dilution Manifold and Support Structure	3
2.	Dilution Cone	4
3.	Control and Monitoring Assembly	5
4.	Flow Diagram, Dilution Sampling System	6
5.	Cyclone Efficiency vs. Particle Size at 10 CFM, Room Temperature	11
6.	Control and Monitoring Assembly Interconnections	13

TABLES

Number		Page
I	Design Objectives for the Sampling System	2
II	Typical System Pressure Drops	7
III	Dilution Orifice and Cyclone Calibration Data	9
IV	System Components, Size and Weight	16
V	Spare Parts List	19

METRIC CONVERSION TABLE

1 ft^3/min (CFM) = 28.32 liters/min (LPM)

1 ft = 0.3048 m

1 in. = 2.54 cm

1 lb_m = 0.4535 kg

1 lb_f = 4.448 N

29.92 in. Hg at 32°F = 760 mm Hg at 0°C

°C = 5/9 (°F - 32)

Section 1

INTRODUCTION

The primary design objective of this apparatus was to provide non-contaminated samples of condensable materials from stack discharges at municipal incinerators and hazardous waste disposal facilities for bioassay. Two opposing design constraints were (1) to provide sufficient quantities of particulate matter within a reasonable sampling time (ie., $\leq$ 1 day) and (2) to provide a transportable instrument that could be operated at various sites. For microbial mutagenicity (Ames) assays, sufficient particulate to obtain 10 to 100 mg of extractable organic material is desirable. This resulted in the design of a 10 cubic feet per minute (CFM) sampling system with a 10:1 dilution ratio. A summary of the design objectives is shown in Table I.

A photograph of the main components of the dilution system and the associated support structure is shown in Figure 1. The support assembly provides a cradle for supporting the dilution manifold and the associated probe (not shown in the photograph). The cradle can be adjusted vertically to position the probe at the selected sampling port. The cyclone, shown at the left end of the dilution manifold, is a modified Source Assessment Sampling System (SASS) cyclone (Blake, 1978). The diluter, located between the cyclone and the first set of flanges, consists of a perforated cone located inside a cylindrical enclosure. The sample air from the cyclone is introduced into the throat of the cone. The dilution air, introduced into the outer shell, is forced through the holes drilled into the cone's surface. A photograph of the cone insert is shown in Figure 2. The perforations in the cone are visible in the photograph. The flanges at either end of the cone provide an airtight seal. The mixing chamber, connected to the right side of the dilution section, allows time for the formation of condensable emissions and directs the gas to a horizontal filter located between the large flanges at the right and bottom of the dilution manifold. The particulate matter is collected on a Teflon coated glass fiber filter and the filtered gas exits through the large shallow manifold under the filter.

The temperatures and pressures of the dilution system are controlled and monitored by means of the control and monitoring assembly shown in Figure 3.

SECTION 2

DETAILED DISCUSSION OF THE SYSTEM

A flow diagram of the dilution sampling system is shown in Figure 4. The four main flow paths include (1) the dilution air, (2) the sample gas, (3) the diluted gas, and (4) the outlet gas. Typical pressure drops for the flow system are listed in Table II. The control and monitoring assembly shown in Figure 3 is provided for controlling and monitoring various temperatures and pressures within the system. The four flow paths within the sampling apparatus are discussed separately below.

Table I. Design Objectives for the Sampling System

Inlet Sample

1. Temperature: < 191°C (375°F)
2. Sample flow: 283 lpm (10 CFM)
3. Removal of particles >2.5 μm with cyclone
4. Glass and Teflon surfaces throughout sample gas processing to minimize contamination

Dilution Gas:

1. Provided by processed ambient air, filtered through HEPA filter and charcoal bed to remove particulates and hydrocarbons
2. Optional air dehumidifier to prevent moisture condensation of diluted air
3. Temperature control to heat dilution gas to normal atmospheric conditions (nominal 75°F, 24°C)
4. Dilution air flow: 2830 lpm (100 CFM) to provide a dilution/sample ratio of 10:1).

Diluter and Mixing Chambers

1. Accelerated mixing instead of normal dilution of effluent discharge of incinerator output into atmosphere
2. Post dilution residence time: 3 seconds
3. Optional section for adsorption denuder

Sample Collection

1. Condensables collected on Teflon-coated glass fiber filter
2. Provide condensables for chemical and biological assay analysis.

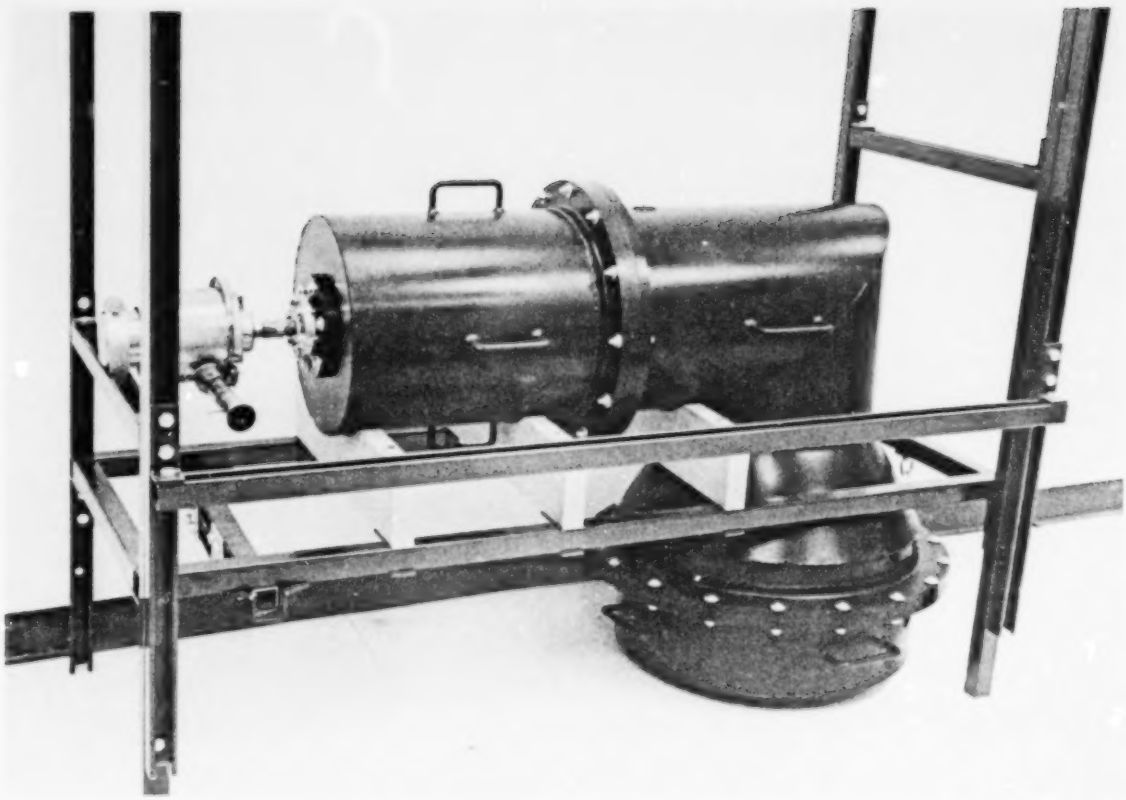

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Figure 1. Dilution Manifold and Support Structure.

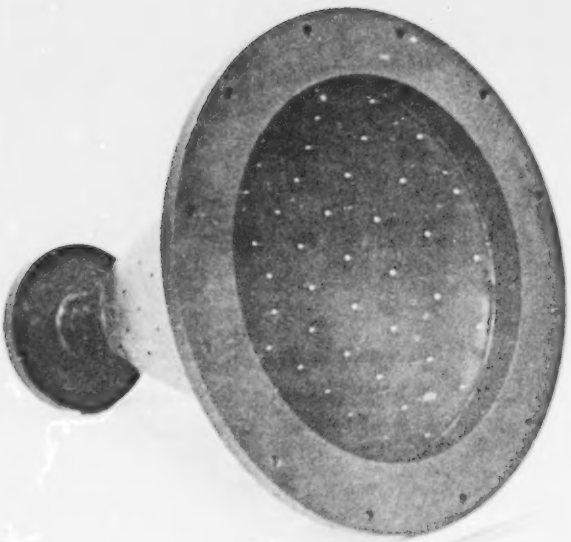

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Figure 2. Dilution Cone.

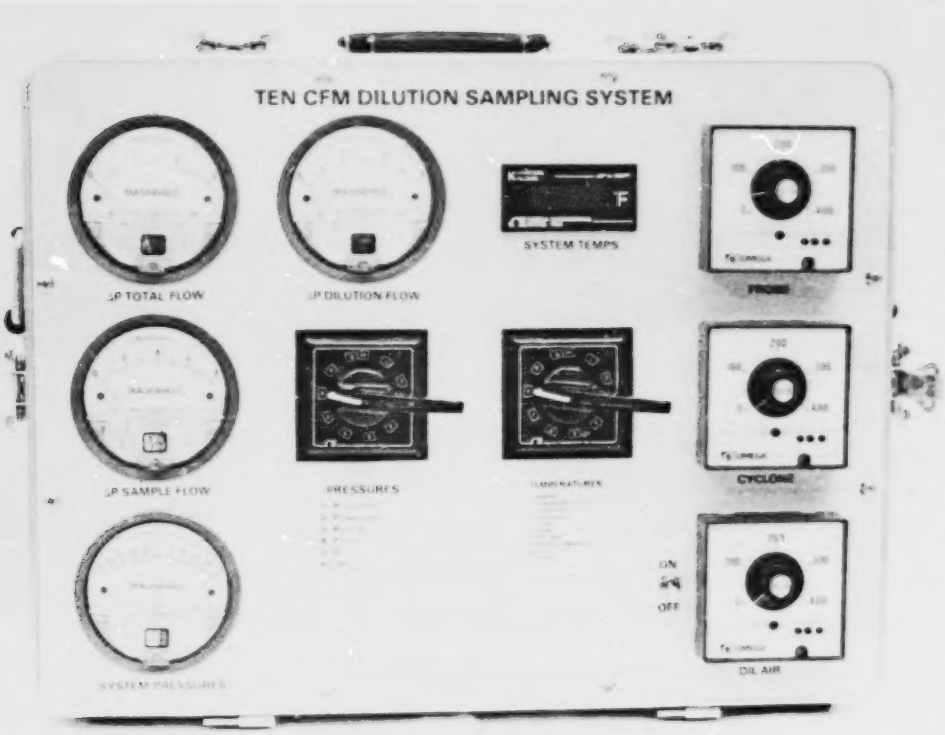

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Figure 3. Control and Monitoring Assembly.

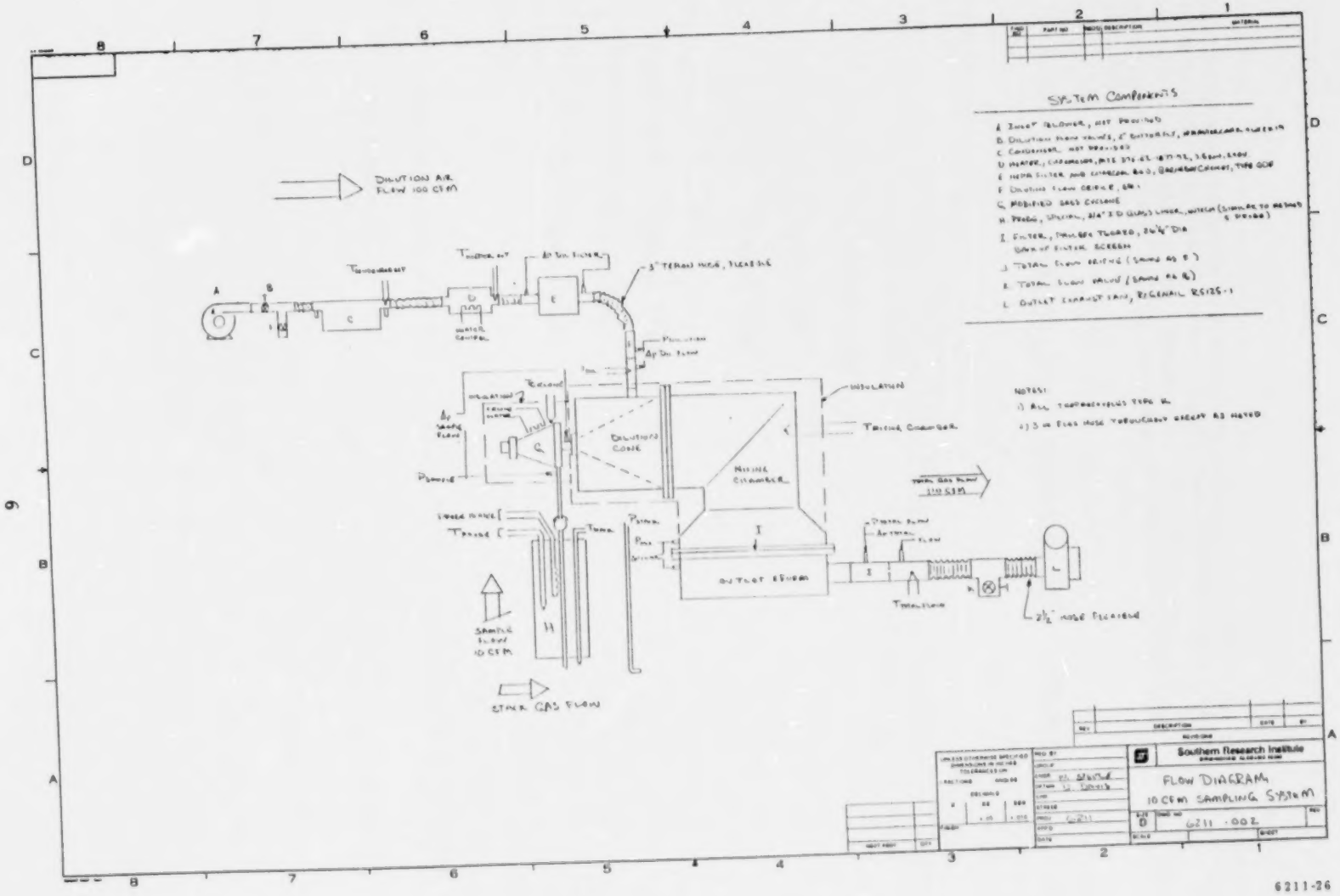

Figure 4. Flow Diagram, Dilution Sampling System.

Table II. Typical System Pressure Drops

The following pressures are shown for reference purposes for the apparatus illustrated in Figure 4.[1] Both sample and dilution gases were derived from ambient conditions in the laboratory. The sample flow was adjusted at approximately 10 CFM and the dilution air was set at 100 CFM. Both filters were clean.

Location	Value (in. H_2O)	(cm. H_2O)
1. $\Delta P_{\text{DILUTION FILTER}}$	1.6	4.1
2. $P_{\text{DILUTION FLOW}}$	-6.0	-15.2
3. $\Delta P_{\text{DILUTION FLOW}}$	2.1	5.3
4. $P_{\text{SAMPLE FLOW}}$	-4.3	-10.9
5. $\Delta P_{\text{SAMPLE FLOW}}$	4.8	12.2
6. P_{MIX}	-11.0	-27.9
7. $\Delta P_{\text{SAMPLE FILTER}}$	2.8	7.1
8. $P_{\text{TOTAL FLOW}}$	-14.0	-35.6
9. $\Delta P_{\text{TOTAL FLOW}}$	2.72	6.9

[1]The locations used for measurement of the pressures are indicated in Figure 4.

DILUTION AIR

The dilution air flow path consists of an optional auxiliary blower (not provided), control valves, an optional condenser (not provided), a heater, a High Efficiency Particulate Air (HEPA) filter, a charcoal bed, and an in-line orifice for measuring flow.

An in-line and bleed valve are provided to control the magnitude of dilution air flow. These consist of two butterfly valves 2 inches in diameter to minimize the associated pressure drops at flow rates of 100 CFM when the valves are fully open. An auxiliary blower may be necessary to provide the required flow of ambient air when the pressure of the sample stack is near or above normal atmospheric pressure. This blower may also be required when the system is turned on or off in order to prevent the reverse flow of gas through the sample filter. In some situations the bleed valve may be used to gradually increase or decrease dilution flow and prevent backflow in the system.

A condenser (not provided) may be required for operating the system during warm or humid atmospheric conditions. The condenser provides a means of cooling and drying the dilution air so, when it is mixed with the sample gas, a typical temperature of 75°F can be obtained with no water condensation. The condenser will be required in situations where the ambient temperature is at or above the desired mixed gas temperature of 75°F or the local humidity is such that the mixed gas is very near or above saturation at 75°F.

A heater is provided for heating the dilution air to a temperature of about 70°F when necessary. The associated controller is located in the control and monitoring assembly.

A HEPA filter and a charcoal bed are provided to avoid contamination of the sample gas due to particulate or vapors (gases) in the dilution air. These are located within a common canister that is sealed against leaks with EPDM (ethyl propylene diene) gasket material. This unit is replaceable.

The dilution air is transported between the above components by means of a 3" flexible hose; a Teflon coated hose section is used between the filter assembly and the flow orifice attached to the diluter. The calibration data for the inlet and outlet dilution orifices at room temperature is given in Table III.

The calibration equation used to define the flow characteristics of the dilution orifices (inlet and outlet) was:

$$\Delta H@_i = \frac{0.9245}{Q^2} \quad \frac{\Delta P(T+460)}{P\,M}$$

where

$\Delta H@_i$ = single point orifice calibration constant
Q = flowrate at orifice conditions, acfm
ΔP = orifice pressure drop, inches H_2O

Table III. Dilution Orifice and Cyclone Calibration Data

Location	Orifice Temperature (°F)	Orifice Inlet Pressure (in. Hg)	Orifice Pressure Drop (in. H_2O)	Flow, Q (ACFM)	Calculated ΔH@ (in. H_2O)
Inlet	75	28.82	0.34	41.215	1.184E-04
Inlet	75	28.53	0.74	61.531	1.168E-04
Inlet	75	28.20	1.23	82.388	1.096E-04
Outlet	75	28.57	0.36	41.576	1.243E-04
Outlet	75	28.13	0.76	62.415	1.183E-04
Outlet	75	27.76	1.28	83.697	1.122E-04
				Average Value ΔH@ =	1.17 E-04
Cyclone	75	29.08	3.00	7.997	2.751E-02
Cyclone	75	28.99	4.00	9.299	2.721E-02
Cyclone	75	28.91	5.00	10.390	2.732E-02
Cyclone	75	28.83	6.00	11.328	2.766E-02
				Average Value ΔH@ =	2.743E-02

T = orifice temperature, °F
P = orifice inlet pressure, inches Hg
M = gas molecular weight (28.97 for standard air)

The calculations for the actual flow in the system are discussed later in this section.

SAMPLE GAS

The sample gas is transported to the dilution manifold by a nozzle, a probe with a 3/4 inch ID glass insert, and a modified SASS cyclone. The 45° beveled surface of the glass nozzle should face into the flue gas stream. The probe is a variation of a EPA Method 5 probe (Rom, 1972). The large bore glass insert is wrapped with a heater tape and has an outer stainless steel shield for mechanical support and protection. The probe is connected to a modified SASS cyclone by means of a glass ball and stainless steel socket joint. The modifications to the cyclone consisted of changing the inlet to a female ball socket and replacing the right-angle exit with a 3/4 inch vertically-mounted exit tube. The efficiency of particulate removal in the cyclone is shown in Figure 5. This data indicates a D_{50} (cut diameter) of 1.8 μm at room temperature. This value may shift upward or downward in particle size at the higher sample temperatures expected in the field depending on the actual operating conditions. Pressure taps were provided at the inlet and outlet of the cyclone to provide a measurement of the sample gas flow; the calibration data for the cyclone flow at 75°F (approximately ambient temperature) are given in Table III. The calculation of the actual flow is discussed later in this section. Under stack sampling conditions the probe and cyclone are heated to maintain the sample gas at the flue gas temperature. The temperature controllers are located on the control and monitoring assembly. The outlet of the cyclone is connected to the dilution chamber through a Teflon insulator to minimize temperature losses of the heated cyclone to the cooler dilution assembly.

DILUTED GAS

The purpose of the dilution manifold is (1) to dilute the sample gas rapidly and uniformly, (2) to provide a mixing or dwell chamber that allows suitable reaction time for the condensable materials, and (3) to collect the resulting particulate materials on a glass fiber filter which is Teflon-coated so the filter will be non-reactive with the collected material.

A nominal 10:1 dilution of the sample gas is achieved by means of the dilution cone shown in Figure 2. The sample gas is introduced through the throat of the cone and the dilution air is forced through the outer surface of the perforated cone. The perforations consist of 136 holes, 0.166 inches in diameter, distributed somewhat uniformly over the surface of the cone. Laboratory measurements of the particulate concentration with an Electrical Aerosol Analyzer (EAA) while the system sampled room air indicated a uniform dilution of the sample gas at the exit of the dilution cone. The diluted gas subsequently enters a dwell chamber that allows a residence time of approximately 3 seconds. The gas from the diluter flows horizontally before following a right angle into a vertical flow section that contains a horizontally mounted circular filter approximately 0.01 inches thick. The active filter diameter is nominally 22.5 inches. The large filter size was

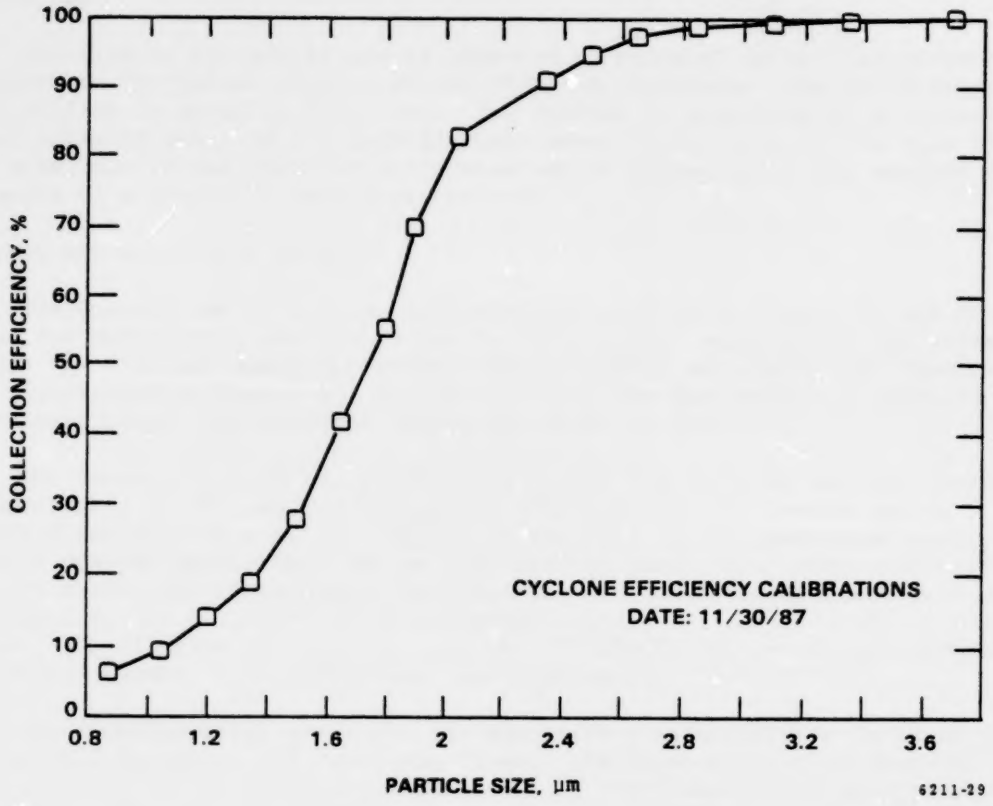

Figure 5. Cyclone Efficiency vs. Particle Size at 10 CFM, Room Temperature.

used to minimize the associated pressure drop (approximately 3 in. H_2O gauge) at a flow of 110 CFM. The filter is sealed between two flanges by compressing the edges of the filter from 0.010 inches to approximately 0.005 inches. A heavy duty screen is provided below the filter for support during the sampling period. An outlet transform below the filter directs the filtered gas to the outlet system.

OUTLET GAS

The flow of the outlet gas is measured by means of an orifice assembly attached to the outlet section of the dilution transform. The calibration of this orifice is given in Table III. The orifice is connected to a control bleed valve by means of a 3 inch flexible hose. This valve is the same type and size used in the dilution air system and is connected to the exhaust pump by means of a short 2.5 inch flexible hose.

CONTROL AND MONITORING ASSEMBLY

The control and monitoring assembly, illustrated in Figure 3, has provisions for controlling and monitoring various system temperatures and pressures within the dilution sampling system. The pneumatic and electrical connections are illustrated in Figure 6. The locations of the monitored and measured parameters within the dilution system are shown in Figure 4.

The temperatures of the probe, cyclone and the dilution air are controlled automatically to the desired set point. The dilution air heater can be disabled manually by a switch located to the left of the associated controller. Various system temperatures can be monitored by means of a temperature display and the associated thermocouple switch. The monitored temperatures include (1) ambient, (2) dilution air at condenser outlet, (3) dilution air at heater outlet, (4) dilution air at flow orifice, (5) stack, (6) probe, (7) cyclone, (3) mixing chamber, (9) outlet gas, and (10) spare.

Three differential pressures are monitored continuously to indicate the the sample, dilution, and total gas flows. The flow calibration data for determination of the calibration constants at room temperature were given in Table III. The flow at standard conditions can be calculated from the equations discussed below.

Dilution and Total Gas Flow

Determination of the dilution and total gas flow can be made using the following equation:

$$\Delta H = 1.083\ (\Delta H@)\ \left(\frac{T_{DA}}{T^2_{STD}}\right)\ \left(\frac{P^2_{STD}}{P_{BAR}-\Delta P_{OA}/13.6}\right)\ (M_A)\ (Q_{STD})^2$$

Substituting the known values reduces the equation to:

$$\Delta H = 1.18 \times 10^{-5}\ \left(\frac{T_{DA}}{P_{BAR}-\Delta P_{OA}/13.6}\right)\ (Q_{STD})^2$$

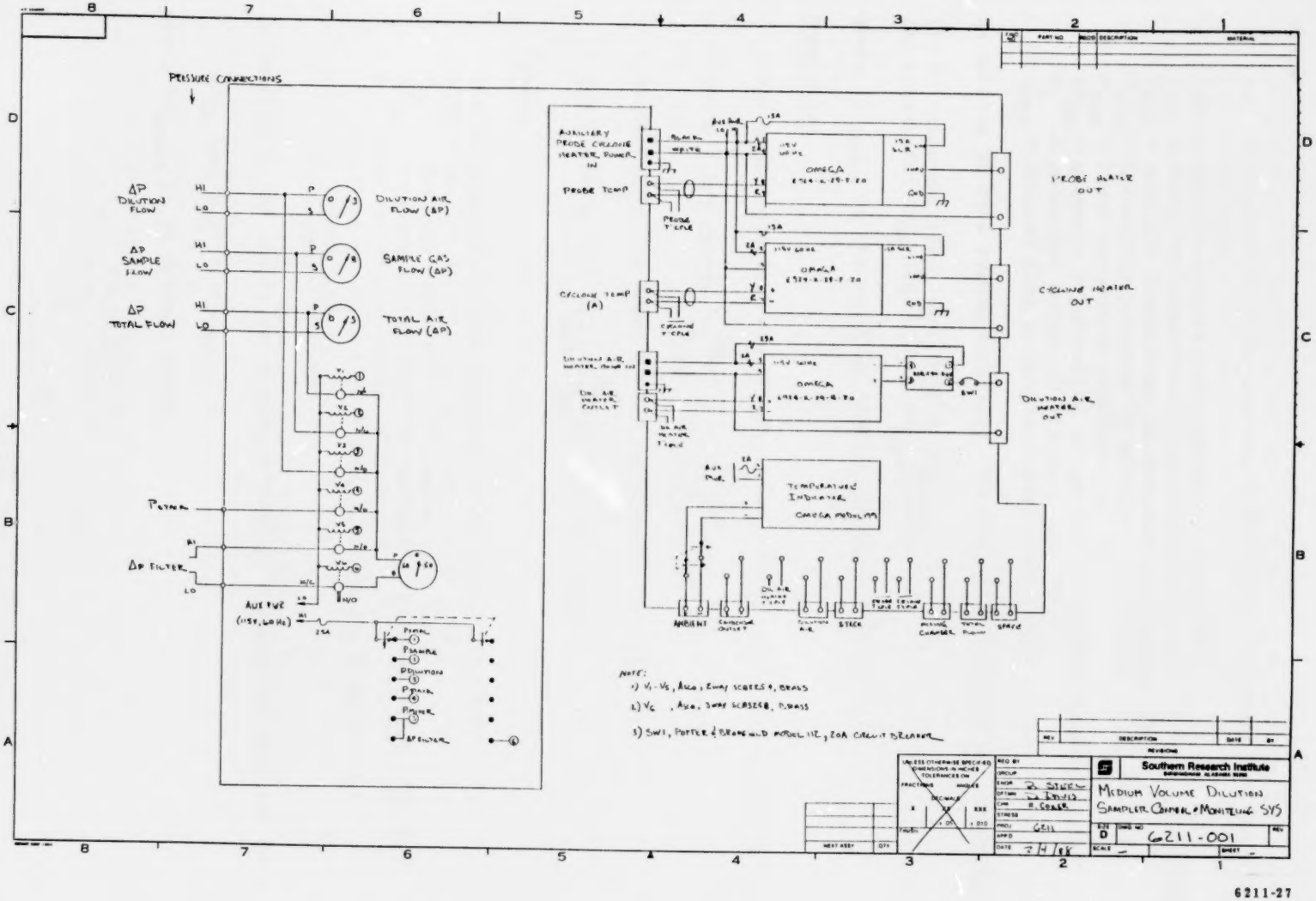

Figure 6. Control and Monitoring Assembly Interconnections.

where

ΔH = required orifice pressure differential to obtain the desired flow; in. H_2O
$\Delta H@$ = orifice calibration constant; 1.17×10^{-4}
T_{DA} = absolute temperature of dilution/total air; °R = [T_{DA} (°F)+460]
T_{STD} = absolute temperature at standard conditions; 528°R
P_{STD} = barometric pressure at standard conditions; 29.92 in. Hg
P_{BAR} = local barometric pressure; in. Hg
ΔP_{OA} = pressure differential to ambient at orifice inlet; in. H_2O
M_A = molecular weight of standard air; 28.95
Q_{STD} = desired flow at standard conditions; SCFM

In setting up this system initially, the following settings are suggested:

(1) dilution air; ΔP_{OA} (in. H_2O) = ΔP_{STACK} - 4
(2) total air; ΔP_{OA} (in. H_2O) = ΔP_{STACK} - 12

where ΔP_{STACK} is the stack to ambient pressure differential.

Sample Gas

The sample gas flow can be calculated using the following equation:

$$\Delta CY = 1.083\ (\Delta CY@)\ \left(\frac{T_{CA}}{T^2_{STD}}\right)\ \left(\frac{P^2_{STD}}{P_{BAR}-\Delta P_{CA}/13.6}\right)\ (M_W)\ (Q_{STD})^2$$

Substituting the known values reduces the equation to:

$$\Delta CY = 9.54 \times 10^{-5}\ \left(\frac{T_{CA}}{P_{BAR}-\Delta P_{CA}/13.6}\right)\ (M_W)\ (Q_{STD})^2$$

where

ΔCY = required cyclone pressure differential, in. H_2O
$\Delta CY@$ = cyclone calibration constant; 2.743×10^{-2}
T_{CA} = absolute temperature of sample gas, °R
ΔP_{CA} = pressure differential to ambient at cyclone inlet; in. H_2O
M_W = wet molecular weight of flue gas
= $\left[(17 * \%\ H_2O) + \left[(32 * \%\ O_2 + 44 * \%\ CO_2 + 28 * \%\ N_2) * \frac{(100-\%\ H_2O)}{100}\right]\right)/100$

In setting up the sample gas system initially, a suggested starting point is

ΔP_{CA} (in. H_2O) = ΔP_{STACK} - 4

where ΔP_{STACK} is as defined above.

Various system pressures can be monitored by means of a pressure indicator and the associated selector switch located on the control and monitoring assembly. This switch controls solenoid valves that apply the appropriate system pressure taps to the pressure indicator. The electrical and pneumatic connections are illustrated in Figure 6. The pressures that can be individually monitored include (1) total flow, (2) sample flow, (3) dilution flow, (4) stack, (5) mixing chamber, and (6) differential pressure drop across the sample filter.

SECTION 3

ASSEMBLY AND OPERATING PROCEDURES

The portability of the sampling system is enhanced by the modular construction of the component parts. The size and weight of the various components are listed in Table IV. The dilution manifold and the associated support structure can be disassembled for ease of transportation. This section outlines precautions that should be observed during the assembly and operation of the sampling system.

The body of the dilution manifold consists of 0.090 inch aluminum walls and 0.75 inch aluminum flanges. This assembly, including the backup filter screen, is Teflon coated with a Dupont Teflon-S high temperature primer and two coats of Teflon FEP (fluorinated ethylene propylene copolymer) on the inside and outside surfaces. The black appearance is due to the primer coat; the Teflon topcoats are transparent and have a smooth surface. In order to protect the Teflon coating on the inside and the flange surfaces, the wooden covers provided should be bolted to the flanges when disassembled. The housing for the HEPA filter and charcoal bed as well as the inside of the cyclone are also Teflon coated. A Teflon hose is used to transport the dilution air between the filter and the dilution manifold.

The components of the support structure are identified to facilitate assembly. Three wooden cradles are provided to support the assembled dilution manifold; heavy duty elastic cords are used to hold the transform on the cradles. The support structure must be lowered over the 27 inch outlet flange associated with the sample filter since the flange will not fit through the side rails of the structure. Once the manifold is supported, the filter can be accessed by removing the bolts from the filter flange and removing the entire outlet transform between the side legs. During assembly, care should be taken to avoid damaging or contaminating the Teflon-coated glass fiber filter. The filter should be trimmed to a diameter of 26.125 inches and installed centrally within the recessed surface of the filter flange. Installation must ensure that all mixed gases go through the filter and that they do not go around an unclamped edge of the filter.

After the dilution transform has been installed on the support frame, the cyclone should be attached to the face of the diluter. The height of the transform assembly and cyclone can be adjusted vertically, by sliding the side

Table IV. System Components, Size and Weight

Item	Approximate Outside Dimension	Weight (lb)
1. Heater	12" x 7" x 12"	35
2. Dilution Air Filter	12" x 14" x 12"	50
3. Dilution and Total Flow Orifice	3.5" diameter x 19"	5
4. Cyclone	8" diameter x 10"	5
5. Probe	1.5" diameter x 37"	12
6. Support Frame for Dilution	30" x 55" x 64"	110
7. Dilution Transform (assembled)	66" x 27" x 37"	80
8. Dilution Transform Components		
a. Diluter transform	19" diameter x 34"	25
b. Mixer transform	27" x 24" x 30"	30
c. Outlet transform	27" diameter x 8"	14
d. Sample filter backup screen	23 11/32" diameter x 1/2"	11
9. Outlet Exhaust Fan	15" x 14" x 14"	75
	TOTAL	452

rails up and down the legs of the support structure, in order to accommodate the desired sampling port. The cyclone can be rotated to accommodate sampling from ports located below the sampling platform or at angles other than horizontal or vertical. Once the height of the dilution manifold is adjusted, the rear of the cyclone should be supported with a clamp attached to a front rail. At this point, the leak test, outlined in the following paragraph, should be performed. A second clamp is provided that supports one end of the probe; it is attached to an additional side rail for horizontal probe access or to a rail directly under the cyclone for vertical probe access. The glass probe is a special order item and should be handled with extreme care to prevent breakage. The adjustment of the probe clamp should be done carefully to avoid stressing the glass components while maintaining a good seal at the ball joint. The probe nozzle should be oriented in the duct such that the 45° beveled surface of the probe extender faces into the gas stream. An auxiliary pitot-type probe is required to measure the internal duct pressure.

Once the dilution transform and cyclone have been assembled at the site, a leak test should be performed as follows: (1) connect the Teflon dilution hose from its normal position on the manifold to the manifold's outlet (2) plug the cyclone inlet with a rubber stopper and connect the control unit to the manifold (3) connect an auxiliary vacuum pump to the dilution manifold and reduce inside pressure to approximately -35 in. H_2O (4) clamp the system and monitor pressure of P_{MIX}. If the inlet vacuum cannot be sustained, pressurize the manifold and locate leaks with a liquid leak detector. Note: Pressures and vacuum should be applied and released slowly to avoid rupturing the sample filter.

The system components (ie, heaters, blowers, filters, etc.) are interconnected by means of 3 inch flexible hoses; a Teflon-lined hose is supplied for the dilution inlet gas to the dilution manifold. The dilution manifold and mixing chamber should have an insulated jacket to maintain the mixed gases at approximately 75°F.

The following lists some additional precautions that should be exercised during the preparation and execution of a sampling test:

1. Replace HEPA filter and charcoal bed prior to testing at each new site (seal the external cover and the HEPA filter internally with a Teflon joint sealant used for making gaskets).

2. Avoid rupturing sample filter due to reverse gas flow by using dilution air blower. Insure differential pressure due to normal flow across sample filter > 3 in. H_2O at the beginning of the test.

3. Maintain probe and cyclone as near to stack temperature as feasible. (Note: Cyclone should not be heated above 375°F to avoid damaging internal Teflon coating.)

4. Measure dew point of exhaust air and insure mixing chamber temperature is greater than dew point temperature.

5. Handle filter carefully (rubber surgical gloves are suggested) and avoid external contamination. The condition of the filter (i.e. ruptures, unsealed edges) should be noted at the completion of each test. Fold and store filter in a sealed glass or Teflon container at end of test.

A list of suggested spare parts and equipment for field testing is tabulated in Table V.

Table V. Spare Parts List

Part	Part Number	Quantity
"O" Rings		
1. cyclone/diluter insulator flange	Parker 2-333-V747-75, viton	1
2. diluter cone flange (small)	Parker 2-343-V747-75, viton	1
3. diluter cone flange (large)	Parker 2-461-V747-75, viton	2
4. sample filter flange	Parker 2-475-V747-75, viton	1
5. cyclone, large	Parker 2-260-V747-75, viton	1
6. cyclone, small	Parker 2-238-V747-75, viton	1
Filter Material HEPA filter cartridges	Flanders, airpure, Stock #7C 10A, size C	1
Charcoal	Activated charcoal, 7FX	5 lb
3 in. Flexible Hose Dilution inlet, teflon lined	McMaster-Carr, 5497K45	12 ft hose
All others	Flexaust or equivalent	25 ft
Probe Glass Liner	Ace glass, 3/4 in. ID, 1 in. OD, 8ft long with 35/20 ball attached	1 ea.
Filter Material Teflon coated glass fiber	Pallflex T60A20	12.5 ft, 40 in. wide (5 ea. filter @ 26 1/8 in. dia.)
Miscellaneous		
Teflon pipe tape		10 rolls
Teflon joint sealant for gasketing		25 ft
Tygon or rubber surgical tubing, 3/16 in. ID		50 ft

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